Supernova neutrinos: production, propagation and oscillations *

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I shall review some of the recent results concerning the astrophysics of a core collapse supernova (SN) and neutrino oscillations. Neutrinos play an important role in the SN explosion, and they also carry most of the energy of the collapse. The energy spectra of neutrinos and antineutrinos arriving at the Earth incorporate information on the primary neutrino fluxes as well as the neutrino mixing scenario. The analysis of neutrino propagation through the matter of the supernova and the Earth, combined with the observation of a neutrino burst from a galactic SN, enables us to put limits on the mixing angle θ_{13} and identify whether the mass hierarchy is normal or inverted. The neutrino burst also acts as an early warning signal for the optical observation, and in addition allows us to have a peek at the shock wave while still inside the SN mantle.

1. Introduction

Neutrinos are crucial to the life and afterlife of a SN. The current understanding of the SN explosion mechanism suggests that neutrinos are responsible for reviving the stalled shock and causing the eventual explosion [1,2,3]. The protoneutron star cools through the emission of neutrinos, which account for nearly 99% of the gravitational binding energy of the collapse. The observation of the neutrino burst from a galactic SN would shed light on many of the outstanding questions in neutrino oscillation physics and astrophysics.

Neutrinos undergo flavour conversions on their way out through the mantle and envelope of the star, through the interstellar space, and possibly even through some part of the Earth before arriving at the detector. The spectra of these neutrinos carry information about the two mass squared differences and the ν_e flavour component in the three mass eigenstates. Of course this information comes convoluted with the primary fluxes of the neutrinos produced inside the star, and the extraction of the mixing parameters depends crucially on our understanding of these primary fluxes.

Recent simulations [4] indicate that the mean energies and relative fluxes of neutrino species are significantly different from the traditionally accepted values. Even these have large uncertainties, so that only a few of the robust features of these spectra can be used with confidence to extract the mixing parameters. In spite of this limitation, it has been argued [5,6] that the observations of the ν_e and $\bar{\nu}_e$ spectra at the detectors on Earth may reveal the type of the neutrino mass hierarchy and limit the value of θ_{13}. In addition, significant modifications of neutrino spectra that can take place if the neutrinos travel through the Earth matter before reaching the detector can provide concrete signatures for some of the neutrino mixing scenarios [7,8,9].

Since neutrinos are expected to arrive hours before the optical signal from the SN, the neutrino burst serves as an early warning [10]. At a water Cherenkov detector the size of SuperKamiokande (SK), the burst can also be used to locate the SN to within a few degrees in the sky [11,12,13], so that optical telescopes can be pointed in the appropriate direction.

The neutrino burst also plays an important role in our understanding of the supernova explosion mechanism. Since neutrinos come unscattered from deep within the sky, we are really looking through them at deep internal regions of the exploding star. The time evolution of neutrino spectra have information about the shock wave

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propagation encoded in them, which can be extracted at least for certain neutrino mixing scenarios [14,15,16].

This article is organized as follows. Sec. 2 discusses the neutrino emission during the core collapse and cooling, the role of neutrinos in SN explosion, and the flavour dependence of primary fluxes and spectra. Sec. 3 describes the neutrino flavour conversions inside the star and the Earth. Sec. 4 discusses the extraction of neutrino mixing parameters from the observed neutrino spectra, pointing out how Earth matter effects can help in identifying mixing scenarios independently of the uncertainties in the initial fluxes. Sec. 5 describes how accurately the neutrino burst can point to the SN in advance and how features of the shock wave can be observed through neutrinos. Sec. 6 concludes.

2. Neutrino production and emission

Neutrinos and antineutrinos of all species are produced inside the SN through pair production processes. In addition, ν_e is also produced by electron capture on protons: $pe^- \to n\nu_e$. At densities of $\rho \gtrsim 10^{10}$g/cc, the mean free path of neutrinos is much smaller than the size of the core, so that the neutrinos are not able to stream out freely from the core. Even before the collapse, neutrinos of all species are trapped inside their respective "neutrinospheres" around $\rho \sim 10^{10}$g/cc.

When the iron core reaches a mass close to its Chandrasekhar limit, it becomes gravitationally unstable and collapses. A hydrodynamic shock is formed when the matter reaches nuclear density and becomes incompressible. The shock wave dissociates the nuclei on its way outwards towards the surface of the star. This increases the number of protons available and consequently, the rate of electron capture and ν_e production. As a result, when the shock wave passes through the ν_e neutrinosphere, a short ν_e "neutronization" burst is emitted, which lasts for ~10 ms.

The object below the shock wave, the "protoneutron star," then cools down with the emission of neutrinos of all species. This emission takes place over a time period of $t \sim 10$ s. The first 0.5–1 s correspond to the "accretion phase," during which the matter keeps on accreting over the inner core, emitting most of its gravitational energy in neutrinos. Later the protoneutron star slowly contracts, cools and deleptonizes during the so-called "Kelvin – Helmholtz cooling phase" [2]. The neutrinos emitted during these 10 s exit the star much before the shock wave blows the envelope up, so the neutrinos arrive at the Earth a few hours before the optical signal.

2.1. Role of neutrinos in explosion

The original shock wave is not able to cause a SN explosion. It loses energy in disintegrating iron nuclei, and the increased ν_e emission during the neutronization burst dampens the shock. However, as more stellar matter falls onto the collapsed inner core, the shock is pushed to higher radii and the density and temperature behind the shock decrease. At the same time, the central core begins to settle and heats up, thus radiating more energetic neutrinos. This results in ~10% of ν_e and $\bar{\nu}_e$ getting absorbed by free neutrons and protons behind the shock. The neutrino energy is then transferred to the shock, and if this energy deposition is efficient enough, the stalled shock can be revived and drives a "delayed" explosion [1].

The "neutrino heating" is thus crucial for the SN explosion. However, it is found that the energy transfer behind the stalled shock is not efficient enough to produce explosions. There have been no successfully simulated spherically symmetric (1D) explosions that take into account the elaborate transport description [17], and even the addition of convection in the 2D simulations performed with a Boltzmann solver for the neutrino transport fails to cause explosion [3]. This suggests that either there is some missing physics related to the nuclear equation of state and weak interactions in the subnuclear regime, or there is a more fundamental problem with the neutrino driven explosion mechanism. (See [3] for more details.)

2.2. Primary neutrino fluxes and spectra

A SN core acts essentially like a neutrino blackbody source, but small flavour-dependent differences of the fluxes and spectra remain. Since

these differences are very small between $\nu_\mu, \nu_\tau, \bar{\nu}_\mu$ and $\bar{\nu}_\tau$, all these species may be represented by ν_x. We denote the fluxes of $\nu_e, \bar{\nu}_e$ and ν_x at the Earth that would be observable in the absence of oscillations by $F^0_{\nu_e}, F^0_{\bar{\nu}_e}$ and $F^0_{\nu_x}$ respectively. The energy spectra of all these "primary" fluxes may be parametrized by the form [18]

$$F(E) = \frac{\Phi_0}{E_0} \frac{\beta^\beta}{\Gamma(\beta)} \left(\frac{E}{E_0}\right)^{\beta-1} \exp\left(-\beta \frac{E}{E_0}\right) , \quad (1)$$

where E_0 is the average energy, β a parameter that typically takes on values 3.5–6 depending on the flavour and the phase of neutrino emission, and Φ_0 the overall flux at the detector. The values of the total flux Φ_0 and the spectral parameters β and E_0 are different for $\nu_e, \bar{\nu}_e$ and ν_x, and are in general time dependent. These are determined through the transport of neutrinos inside the core and mantle of the SN.

The transport of ν_e and $\bar{\nu}_e$ inside the star is dominated by $\nu_e n \leftrightarrow p e^-$ and $\bar{\nu}_e p \leftrightarrow n e^+$, reactions that freeze out at the energy-dependent "neutrino sphere." The flux and spectrum is essentially determined by the temperature and geometric size of this emission region. The neutron density is larger than that of protons, so that the $\bar{\nu}_e$ sphere is deeper than the ν_e sphere, explaining $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle$.

For ν_x, in contrast, the flux and spectra formation is a three-step process. The dominating source of neutrino scattering is the neutral-current nucleon scattering $\nu_x N \to N \nu_x$. Deep in the star thermal equilibrium is maintained by nucleon bremsstrahlung $NN \leftrightarrow NN\nu_x\bar{\nu}_x$, pair annihilation $e^- e^+ \leftrightarrow \nu_x \bar{\nu}_x$ and $\nu_e \bar{\nu}_e \leftrightarrow \nu_x \bar{\nu}_x$, and scattering on electrons $\nu_x e^- \to e^- \nu_x$. The freeze-out sphere of the pair reactions defines the "number sphere," that of the energy-changing reactions the "energy sphere," and finally that of nucleon scattering the "transport sphere" beyond which neutrinos stream freely.

Until recently all simulations simplified the treatment of ν_x transport in that energy-exchange was not permitted in νN-scattering, $e^- e^+$ annihilation was the only pair process, and $\nu_x e$-scattering was the only energy-exchange process. However, it has been found that nucleon recoils are important for energy exchange, nucleon bremsstrahlung is an important pair process, and $\nu_e \bar{\nu}_e \to \nu_x \bar{\nu}_x$ is far more important than $e^- e^+ \to \nu_x \bar{\nu}_x$ as a $\nu_x \bar{\nu}_x$ source reaction [18,19,20]. As a result, the recent predictions for ν_x fluxes differ significantly from the traditionally used ones.

Table 1
Model dependence of primary fluxes

Model	$\langle E_0(\nu_x) \rangle$	$\frac{\Phi_0(\nu_e)}{\Phi_0(\nu_x)}$	$\frac{\Phi_0(\bar{\nu}_e)}{\Phi_0(\nu_x)}$
Garching	18	0.8	0.8
Livermore	24	2.0	1.6

The model dependence of the fluxes is evidenced by the comparison of typical values of the parameters in two models as shown in Table 1. The first is motivated by the recent Garching calculation [4] that includes all relevant neutrino interaction rates, including nucleon bremsstrahlung, neutrino pair processes, weak magnetism, nucleon recoils and nuclear correlation effects. The second is the result from the Livermore simulation [21] that represents traditional predictions for flavour-dependent SN neutrino spectra that have been used in many analyses. Both the models agree on $\langle E_0(\nu_e) \rangle \approx 12$ MeV and $\langle E_0(\bar{\nu}_e) \rangle \approx 15$ MeV, and have consistent β values, but they differ widely on $\langle E_0(\nu_x) \rangle$ and the ratios of fluxes. In particular, the equipartition of energy assumed in the Livermore model is not a feature of the Garching model.

In the light of the model dependence, it is important to make sure that the inferences drawn from the observed neutrino spectra do not depend strongly on the exact model parameters.

3. Flavour conversions in matter

3.1. Resonant conversions inside the star

Neutrinos, while freestreaming out of the core, encounter matter with densities ranging from 10^{10}g/cc to almost zero. Matter effects on the neutrino mixing, and hence on the flavour conversions, are crucial. Indeed, the flavour conversions take place mainly in the resonance layers, where $\rho_{\rm res} \approx m_{\rm N} \Delta m^2_i \cos 2\theta / (2\sqrt{2} G_{\rm F} Y_{\rm e} E)$. Here Δm^2_i and θ are the relevant mass squared differ-

Table 2
Survival probabilities for neutrinos, p, and antineutrinos, $\bar{p}$, in various mixing scenarios

	Hierarchy	$\sin^2\theta_{13}$	p	$\bar{p}$
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2\theta_\odot$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2\theta_\odot$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2\theta_\odot$	$\cos^2\theta_\odot$

ence and mixing angle of the neutrinos, $m_{\rm N}$ is the nucleon mass, $G_{\rm F}$ the Fermi constant and $Y_{\rm e}$ the electron fraction. In contrast to the solar case, SN neutrinos must pass through two resonance layers: the H-resonance layer at $\rho_{\rm H} \sim 10^3$ g/cc corresponds to $\Delta m^2_{\rm atm}$, whereas the L-resonance layer at $\rho_{\rm L} \sim 10$ g/cc corresponds to $\Delta m^2_\odot$. This hierarchy of the resonance densities, along with their relatively small widths, allows the transitions in the two resonance layers to be considered independently [5].

When neutrino mixing is taken into account, the ν_e and $\bar{\nu}_e$ fluxes arriving at a detector are

$$F_{\nu_e} = pF^0_{\nu_e} + (1-p)F^0_{\nu_x} \ , \qquad (2)$$

$$F_{\bar{\nu}_e} = \bar{p}F^0_{\bar{\nu}_e} + (1-\bar{p})F^0_{\nu_x} \ , \qquad (3)$$

where p and $\bar{p}$ are the survival probablilities of ν_e and $\bar{\nu}_e$ respectively.

The neutrino survival probabilities can be characterized by the degree of adiabaticity of the resonances traversed, which are directly connected to the neutrino mixing scheme. In particular, whereas the L-resonance is always adiabatic and appears only in the neutrino channel, the adiabaticity of the H-resonance depends on the value of θ_{13}, and the resonance shows up in the neutrino or antineutrino channel for a normal or inverted mass hierarchy respectively. Table 2 shows the survival probabilities in various mixing scenarios. For intermediate values of θ_{13}, i.e. $10^{-5} \lesssim \sin^2\theta_{13} \lesssim 10^{-3}$, the survival probabilities depend on energy as well as the details of the density profile of the SN.

Scenarios A, B and C are the ones that can in principle be distinguished through the observation of a SN neutrino burst.

3.2. Oscillations inside the Earth matter

If the neutrinos travel through the Earth before reaching the detector, the neutrinos undergo oscillations inside the Earth and the survival probabilities change. This change however occurs only in those scenarios in Table 2 where the value of the survival probability is nonzero. The expressions in this section are to be understood in that context.

For antineutrinos that pass only through the mantle with roughly a constant density, the survival probability $\bar{p}^D$ is

$$\bar{p}^D \approx \cos^2\theta_{12} + \bar{A}_m \ \sin^2\left(\overline{\Delta m^2_m} L_m y\right) \ . \qquad (4)$$

where $\overline{\Delta m^2_m}$ is the mass squared difference between $\bar{\nu}_1$ and $\bar{\nu}_2$ inside the mantle in units of 10^{-5} eV^2, and L_m is the distance traveled through the mantle in units of 1000 km. The "inverse energy" parameter y is defined as $y \equiv 12.5$ MeV$/E$ where E is the neutrino energy. The coefficient of the oscillating term is $\bar{A}_m \equiv -\sin 2\theta_m \sin(2\theta_m - 2\theta_{12})$.

When neutrinos travel through both the mantle and the core, the sharp density jumps give rise to the survival probability of the form

$$\bar{p}^D \approx \cos^2\theta_{12} + \sum_{i=1}^{7} \bar{A}_i \sin^2(\phi_i/2) \qquad (5)$$

in the two-layer model of the Earth, where the coefficients $\bar{A}_i$ are functions of the mixing angle θ_{12} in vacuum, mantle and core. The phases ϕ_i depend on the distance travelled through the Earth matter and the values of $\overline{\Delta m^2}$ in the mantle and the core [22].

4. Distinguishing between neutrino mixing scenarios

The only SN observed in neutrinos till now, SN1987A, yielded only ∼20 events. Though it confirmed our understanding of the SN cooling mechanism, the number of events was too small to say anything concrete about neutrino mixing (see [23] and references therein). On the other hand, if a SN explodes in our galaxy at 10 kpc from the Earth, we expect ∼10000 events at SK. With the mixing scenarios A, B and C having clearly distinct survival probabilities for ν_e and

$\bar{\nu}_e$, the task of distinguishing between the scenarios naively seems straightforward: measure the neutrino fluxes arriving at the Earth, and determine the values of p and $\bar{p}$.

There are a few major problems, though. With the current detectors, one can obtain a statistically significant and clean spectrum only of $\bar{\nu}_e$, through the inverse beta reaction $\bar{\nu}_e p \to n e^+$ at a water Cherenkov or scintillation detector. It is possible to obtain a clean ν_e spectrum at a heavy water detector like SNO through $\nu_e d \to p\ p\ e^-$, or at a liquid Ar detector through $\nu_e + {}^{40}\mathrm{Ar} \to {}^{40}\mathrm{K}^* + e^-$, but the sizes of the current detectors of these kinds, and hence the number of events expected in them, are very small. A large liquid Ar detector, as suggested in [24], would be very significant, though technologically challenging, in this context.

Secondly, the primary spectra are poorly known. The uncertainties in the values of E_0 for $\nu_e, \bar{\nu}_e$ and ν_x mean that by merely observing a mixed spectrum, it is not possible to determine the extent of ν_x component in it. A number of observables have been suggested [5,6,25] that can distinguish between different scenarios if the primary spectra obey certain form or if the parameters lie within some bounds, but it has turned out to be very difficult to come up with clean observables that do the job independently of any assumption about the primary spectra.

The presence or absence of Earth effects, however, can be exploited to detect model independent signatures of mixing scenarios. Earth effects manifest themselves in two ways. Firstly, the total number of events and the spectral shape changes, this can be checked by comparing the neutrino signal at two or more detectors such that the neurinos travel different distances through the Earth before reaching them. Secondly, Earth effect oscillations are introduced, which may be identified even at a single detector. These two approaches will be illustrated in the next two subsections.

4.1. Comparing signals at multiple detectors

At least one of the existing detectors (SK, SNO or LVD) should observe the SN neutrinos through the Earth for the location of the SN in a large fraction (60%) of the sky [8]. However, for a SN at 10 kpc one can only get a statistical significance of 2–3σ. In order to get a larger significance, at least two detectors of the size of SK or larger are needed [8].

In this context, the km^3 ice Cherenkov detector in Antarctica, IceCube, can be used as a co-detector with SK or its larger version, Hyper-Kamiokande (HK). IceCube is primarily meant for detecting individual neutrinos with energy $\gtrsim 150$ GeV. However, during a galactic SN burst, the number of Cherenkov photons detected by the optical modules would increase much beyond the background fluctuations, so that the burst as a whole can be identified [26]. It is not possible to detect inividual neutrinos and measure their energies, but it is possible to measure the time dependence of luminosity which is proportional to the total number of Cherenkov photons detected. Indeed, for a SN burst at 10 kpc, the luminosity can be determined to a statistical accuracy of $\sim 0.25\%$ [27].

The Earth effects can change the luminosity by upto 10%. So if the neutrinos travel different distances through the Earth before reaching SK/HK and IceCube, the ratio of luminosities at the two detectors can show evidence for the Earth effects. Moreover, for typical numerical SN simulations, the Earth effect is time dependent and most notably differs between the early accretion phase and the subsequent Kelvin–Helmholtz cooling phase by 3–4%. This indicates that there is no need even of the absolute calibration of either of the detectors, one just has to search for a temporal variation of the relative detector signals of a few percent. The large number of optical modules in IceCube renders this task statistically possible [27]. The accuracy of luminosity measurement in SK/HK would be the limiting factor.

The relative locations of SK and IceCube imply that for the SN in a large portion of the sky, it is observed by only one of the detectors through the Earth. This makes the SK/HK–IceCube comparison an interesting prospect.

4.2. Identifying Earth effects at a single detector

The Earth matter effects on supernova neutrinos traversing the Earth mantle give rise to a specific frequency in the "inverse energy" spectrum of these neutrinos, as can be seen by writing the net $\bar{\nu}_e$ flux at the detector using eqs. (3) and (4) in the form

$$F^D_{\bar{\nu}_e} = \sin^2\theta_{12} F^0_{\nu_x} + \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \Delta F^0 \bar{A}_m \sin^2(k_m y/2)\,, \qquad (6)$$

where $\Delta F^0 \equiv (F^0_{\bar{\nu}_e} - F^0_{\nu_x})$ depends only on the primary neutrino spectra, and $k_m \equiv 2\overline{\Delta m^2_m} L_m$. Note that $\bar{A}_m$ depends only on the mixing parameters and is independent of the primary spectra.

The last term in Eq. (6) is the Earth oscillation term that contains a frequency k_m in y, the coefficient $\Delta F^0 \bar{A}_m$ being a relatively slowly varying function of y. The first two terms in Eq. (6) are also slowly varying functions of y, and hence contain frequencies in y that are much smaller than k_m. The dominating frequency k_m is the one that appears in the modulation of the inverse-energy spectrum.

The frequency k_m is completely independent of the primary neutrino spectra, and indeed can be determined to a good accuracy from the knowledge of the solar oscillation parameters, the Earth matter density, and the position of the SN in the sky. Therefore, Earth effects can be identified merely by identifying the presence of this oscillation frequency in the observed spectrum. This may be achieved by taking a Fourier transform of the inverse-energy spectrum and looking for peaks in the power spectrum

$$G_N(k) = \frac{1}{N}\left|\sum_{\text{events}} e^{iky_{\text{event}}}\right|^2 . \qquad (7)$$

The peak corresponding to the oscillation frequency k_m emerges on top of the random background fluctuations. The position of this peak is insensitive to the primary spectra [28].

If both the mantle and the core are crossed before the neutrinos reach the detector, as many as seven distinct frequencies are present in the inverse energy spectrum, as can be see from eq. (5). However only three peaks are dominant in the power spectrum due to the hierarchy in the $\bar{A}_i$ values. The increase in the number of expected peaks leads to an easier identification of the Earth matter effects [22].

The energy resolution of the detector turns out to be crucial in detecting the Earth effect oscillations, since bad energy resolution tends to smear out the modulations in the energy spectrum. The comparison between a simulated megaton water Cherenkov detector and a 32 kt scintillation detector [22] shows that the better resolution of the scintillator detector almost compensates for the much larger water Cherenkov detector size. On the other hand, the worse energy resolution in water Cherenkov detectors does not only imply the need of a larger volume but it also suppresses significantly the peaks at higher frequencies, in contrast to the case of scintillator detectors.

Only scenarios A and C allow observable Earth effects in $\bar{\nu}_e$. Therefore, the observation of a Fourier peak in $\bar{\nu}_e$ eliminates scenario B independent of SN models. Similarly, if earth effects are observed in the ν_e spectrum, scenario A may be eliminated.

5. Neutrinos for SN astrophysics

5.1. Pointing to the SN in advance

Determining the accuracy to which SN can be located in the sky with neutrinos alone is important for two reasons. Firstly, the neutrino burst precedes the optical explosion by several hours so that an early warning can be issued to the astronomical community [10], specifying the direction to look for the explosion. Secondly, in the absence of any SN observation in the electromagnetic spectrum, a reasonably accurate location in the sky is crucial for determining the neutrino Earth-crossing path to various detectors since the Earth matter effects on SN neutrino oscillations may well hold the key to identifying the neutrino mixing scenario.

The best way to locate a SN by its core-collapse neutrinos is through the directionality of the elastic scattering $\nu e^- \to \nu e^-$ events in a water Cherenkov detector such as SK [11,12]. The directionality of this reaction is primarily limited

by the angular resolution of the detector and to a lesser degree by the kinematical deviation of the final-state electron direction from the initial neutrino.

The pointing accuracy is further strongly degraded by the inverse beta reactions $\bar{\nu}_e p \to n e^+$ that are nearly isotropic and about 30–40 times more frequent than the elastic scattering events. Recently it was proposed to add to the water a small amount of gadolinium, an efficient neutron absorber, that would allow one to detect the neutrons and thus to tag the inverse beta reactions [29]. Removing this major background would still leave one with the nearly isotropic oxygen reaction $\nu_e + {}^{16}\mathrm{O} \to \mathrm{X} + e^-$. No clean separation of this background is possible.

The pointing accuracy also has a weak dependence on the neutrino mixing scenario. It has been found [13] that, for the "worst case" mixing scenario and for the tagging efficiency $\epsilon_{\rm tag} = 0$, at 95% C.L. the pointing accuracy at SK is 7.8°, which improves to 3.6° for $\epsilon_{\rm tag} = 80\%$ and 3° for $\epsilon_{\rm tag} = 1$. Thus, neutron tagging results in nearly a factor of 3 improvement in the pointing angle, which corresponds to almost an order of magnitude improvement in the area of the sky in which the SN is located.

5.2. Tracking the shock wave in neutrinos

The passage of the shock wave through the density of the H-resonance ($\rho \sim 10^3$ g/cc) a few seconds after the core bounce may break adiabaticity, thereby modifying the spectral features of the observable neutrino flux. Therefore, it is conceivable that a neutrino detector can measure the modulation of the neutrino signal caused by the shock-wave propagation, an effect first discussed by Schirato and Fuller in a seminal paper [14] and elaborated by a number of subsequent authors [6,15,30]. Since the density of the H-resonance depends on energy, the observation of such a modulation in different neutrino energies would allow one to trace the shock propagation. On the other hand, the occurrence of this effect depends on the sign of Δm^2_{31} and the value of θ_{13}, so that observing it in the $\bar{\nu}_e$ spectra, the experimentally most accessible channel, would imply that the neutrino mass ordering is inverted and that $\sin^2\theta_{13} \gg 10^{-5}$. This corresponds to the elimination of scenarios A and C.

Some time after the onset of the explosion a neutrino-driven baryonic wind develops and collides with the earlier, more slowly expanding supernova ejecta. This gives rise to a "reverse shock". This is a generic feature of all SN simulations, although the exact propagation history depends on the detailed dynamics during the early stages of the supernova explosion. The simultaneous propagation of a direct and a reverse shock wave manifests itself in a "double dip" feature in the time evolution of observables like the average neutrino energy and the number of events [16].

If the time evolution of the number of events in different energy bins is observed, the positions of the two dips in time can be connected to the positions of the forward and reverse shock. Indeed, the number of shock waves present in a region with any given density $\sim 10^3$ g/cc can be extracted from the data by considering the time evolution of the number of events in the energy bin corresponding to that resonant density [16]. An extrapolation would allow one to trace the positions of the forward and the reverse shock waves for times between 1–10 s. Since the neutrino conversion probabilities are energy dependent during the passage of the shocks through the H-resonance, neutrino oscillations can be detected even if the energy spectra of different neutrino flavours have the same shape but different luminosities.

6. Hoping for a catastrophe

The observation of neutrinos from a core collapse SN is expected to reap a rich scientific harvest. It will immensely improve our understanding of SN astrophysics. If the value of θ_{13} and the type of neutrino mass hierarchy is already determined at terrestrial experiments, concrete information on the primary neutrino fluxes will be obtained. On the other hand, if the burst takes place before the mixing parameters are measured, the limits obtained can guide us in deciding on the design parameters of future long baseline experiments.

A galactic SN burst is a rare phenomenon, ex-

pected to occur only 2–3 times in a century. It is therefore imperative that we are ready with suitable long term detectors that will observe the relevant signals. In the meanwhile, better theoretical understanding of neutrino transport inside the SN, combined with more accurate measurements of the neutrino mixing parameters, will equip us for making the most of the cosmic catastrophe.

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